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Cognitive Engineering: Toward a Workable Concept of Mind

It seems plain to me now that the "cognitive revolution" . . . was a response to the technological demands of the Post-Industrial Revolution. You cannot properly conceive of managing a complex world of information without a workable concept of mind.

—Bruner (1983, p. 63)

Perhaps no one has understood the depth to which the ever-increasing technological nature of the human ecology has shaped psychological theory better than Jerome Bruner. In his memoir *In Search of Mind* (1983), Bruner shared his reflections on the origins of the cognitive revolution. Although a great many factors may have played a role (e.g., Chomsky, 1959; Miller, 1956; Newell & Simon, 1972), Bruner turns much conventional thinking on its head, implying that scientists had to invent a theory of mind in response to the practical demands of finding coherent ways of understanding and coordinating a largely invented world of people engaged with post–Industrial Revolution technologies. The seeds of this scientific revolution, it seems, were not so much "in the air" as in the digital circuitry and in the need to understand and manage "a complex world of information."

A Workable Concept of Mind

The purpose of this book is to take additional steps toward building what Bruner referred to as a "workable concept of mind." Special emphasis is given here to the word *workable*. The central goal is to provide methods and models that can be fruitfully applied to solving practically relevant problems in human–technology interaction. These problems include designing and evaluating technological interfaces, decision aids, alerting systems, and training technology, as well as supporting human–automation interaction and human–computer interaction. In short, the aim of this book is to provide practical resources for addressing the menagerie of problems making up *cognitive engineering* (Hollnagel & Woods, 1983; Kirlik & Bisantz, 1999; Norman, 1986; Rasmussen, 1986). Along the way, many contributors to this volume also present insights and approaches that may shed light on fundamental problems in the science of adaptive cognition and behavior. This may be especially true when it comes to the challenge of understanding and formally articulating the role of the environment in cognitive theory.

Six themes unite the contributors' orientation toward developing a concept of mind that is both workable and valuable from a cognitive engineering perspective. These themes are illustrated in the selection of research problems, methods, and analysis and modeling techniques presented in the following chapters.

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1. An Ecological or Systems Perspective

Pioneers of the cognitive engineering discipline, such as Rasmussen (1990) and Woods (1995), have emphasized the essential *ecological* character of the cognitive engineering enterprise. What does this mean, and why is it the case? The answers to these questions lie in the nature of the systems studied and the practical problems associated with their analysis and design. Cognitive engineering research is largely concerned with the analysis and design of human–technology systems and the role of technology as a mediator between humans and the external objects and events comprising a work domain. As such, cognitive engineering is fundamentally concerned with systems composed of humans, mediating technologies and task environments, as well as the interactions among these system components. Of all the schools or approaches to psychology relevant to cognitive engineering (and there are many), both the theoretical orientation and unit of analysis presumed by ecological psychology are perhaps best aligned with the task of understanding and supporting the mediated coupling between humans and their environments. By reviewing the Instructions for Authors appearing in each issue of *Ecological Psychology*, one learns that the focus of the discipline is a broad range of psychological problems (perception, cognition, communication, development, learning, etc.), but with one noteworthy constraint. In particular, ecological psychology is concerned with those problems only "to the extent that those problems derive from a consideration of whole animal-environmental systems, rather than animals or environments in isolation from each other."

This broad and inclusive perspective on what it means to take an ecological approach to cognitive engineering is the one presumed in this book. As such, the approach is much in the spirit of the Joint Cognitive Systems tradition in cognitive systems engineering (Hollnagel, Mancini, & Woods, 1986). It is inherently a systems approach in which each element of the human–technology–environment unit of analysis receives attention and treatment during analysis and design and where each element is considered in light of its functional role within the overall human–technology–environment system. Although some authors in this book use the phrase "ecological analysis" to highlight the study of the environmental components of these systems and "cognitive analysis" to highlight the study of the internal or mental activities of their human components, the intended meaning of each term will be clear from context. At this point, suffice it to say that the perspective taken in this book is that a *psychological* theory or model, especially one capable of providing cognitive engineering with a workable concept of mind, should include a description of the "whole" human–technology–environment system and not merely internal cognition.

This systems or ecological orientation toward cognitive engineering has long roots in human factors, and especially within the field of "human–machine systems." As noted by Sheridan (2002, p. 5), shortly after World War II human factors researchers increasingly began to borrow modeling techniques from engineering, such as mathematical theories of estimation, information, decision, and control. They did so "to look at information, control, and decision making as a continuous process within a closed loop that also included physical subsystems—more than just sets of independent stimulus-response relations" (Sheridan, 2002, p. 4). The rationale for including a description of physical subsystems within such models, that is, descriptions of the task environment and any mediating technology, was well expressed by Baron, a human–machine systems engineer: "Human behavior, either cognitive or psychomotor, is too diverse to model unless it is sufficiently constrained by the situation or environment; however, when these environmental constraints exist, to model behavior adequately, one must include a model for that environment" (Baron, 1984, p. 6).

Exactly this point, the need for a psychological model to include an environmental model, was one of the defining features of the theory and method developed by one of ecological psychology's pioneers, Egon Brunswik (1903–1955). As will be discussed in greater detail by Goldstein in the following chapter, Brunswik is perhaps best known for his lens model, whose ecological nature is directly apparent in its symmetrical arrangement as a pair of joined human and environmental models (Brunswik, 1952, 1956; also see Hammond & Stewart, 2001). The pervasive influence of Brunswik's theory of probabilistic functionalism and experimental methodology of representative design is evident throughout this volume.

This is not to imply, of course, that only Brunswik's ecological theory is capable of giving rise to

workable resources for cognitive engineering. For example, Vicente (1999) has drawn heavily and profitably on the ecological theory of James J. Gibson (1979/1986) in the development of his Cognitive Work Analysis and Ecological Interface Design (also see Burns & Hajdukiewicz, 2004) cognitive engineering techniques. As both Vicente (2003) and Kirlik (1995, 2001) have observed, it is possible to view the ecological theories of Brunswik and Gibson to be complementary rather than conflicting, despite what much of the psychological research conducted in each of the two traditions may lead one to believe. As such, one should view the research presented in the current volume, largely grounded in Brunswikian theory, and the research program of Vicente and his colleagues, influenced by Gibsonian theory, as similarly complementary rather than conflicting. Neither subsumes the other with respect to the central problems addressed or the techniques provided. The same could also be said of the distributed cognition approach (e.g., Hollan, Hutchins, & Kirsh, 2000; Hutchins, 1995) and any other framework embodying the ecological notion that the unit of psychological analysis and modeling must span the human–environment boundary if it is to provide cognitive engineering with a workable concept of mind (also see Clark, 2003; Dourish, 2001; Kirlik, 1998; Kirsh, 1996; Olson & Olson, 1991; Zhang & Norman, 1997).

2. An Adaptive, Functional Perspective

Anyone who has ever read (or even better, taught from) Donald Norman's (1988) insightful book *The Psychology of Everyday Things* will almost certainly recognize his characterization of the problems faced by a technology user in terms of bridging a "gulf of execution" and a "gulf of evaluation." How do I get it to work? What is it doing? These are questions we find ourselves asking all to often in our interactions with technology. As one who has graded over a thousand students' answers to "define and give an everyday example" exam questions about these gulfs, I have found that if a student is going to get anything correct on an exam it is likely to be these questions. These concepts are immediately intuitive to anyone who has ever experienced difficulty or frustration when using technology, whether in programming a VCR or the flight control automation in a modern glass cockpit airliner (Degani, Shafto, & Kirlik, 1999; Sarter & Woods, 1992).

One reason the authors of this volume have become attracted to Brunswik's functionalist theory of cognition and behavior is its grounding in exactly these gulfs. In particular, and as explained in greater detail by Goldstein in chapter 2, Brunswik's theory is founded in an examination of the proximal–distal relationships characterizing a person's encounter with the world (also see Tolman & Brunswik, 1935). A technological interface provides us with both proximal, or directly available, information sources and proximal opportunities for action. The intended target of our interaction, however, is all too often distal, or not so directly available to us: a goal state to be achieved by taking a correct sequence of proximal actions, and an understanding of whether we have achieved our goal, which can often be gained only by correctly integrating proximally available information.

In 1972, Newell and Simon began their seminal book, *General Problem Solving,* with an expression of debt to Tolman & Brunswik's (1935) *Psychological Review* article emphasizing the necessity of a detailed analysis of these proximal–distal relations to understand goal-directed behavior. Newell and Simon appreciated the insight that such behavior is typically directed toward distal objects or ends that can be achieved only by the adaptive use of proximal information and action resources. One result was Newell and Simon's characterization of problem solving as a search through a "problem space" to find a series of proximal actions that would lead to distal goals. A problem space is a model of a problem solver's environment.

Every chapter in this volume deals in one way or another with an examination of the proximal–distal relations characterizing or mediating one's encounter with the environment and a parallel examination of the degree to which humans are well adapted to these relations. This is what is meant here by an adaptive, functional perspective on cognition and behavior. There is no initial assumption that people are either well or poorly adapted to the demands and opportunities of any particular situation. Instead, the approach taken in the following chapters is to perform detailed functional analyses of task environments and then empirically measure the degree of adaptivity attained in light of both the cognitive and environmental resources available.

Various chapters in parts IV, V, and VI of this book also examine the relationship between Brunswik's original approach to these problems and more recent yet related adaptive approaches to cognition such as Anderson's (1990) Rational Analysis and ACT-R model (Anderson & Lebiere, 1998), and the Ecological Rationality approach developed by Gigerenzer, Todd, and their colleagues (Gigerenzer, Todd, & the ABC Research Group 1999).

3. Embracing Uncertainty

Another aspect of Brunswik's thinking adopted by the authors in this volume is the idea that the relationship between the human and environment must often be characterized in probabilistic terms. Note, however, that this does not reflect an a priori commitment to probabilism but instead the need to have conceptual and technical resources available for measuring and modeling uncertainty where it is found to exist. Having techniques available to represent the possible probabilistic structure both within a task environment and within the operations of inner cognitive processes is especially important for the purpose of evaluating the adaptivity of behavior, and also when motivating interventions aimed at enhancing it. Why?

First, environmental uncertainty places a ceiling on the accuracy of adaptive behavior in any given instance. As Lipshitz et al. (2001a) have (qualitatively) put it, "Uncertainty is intimately linked with error: the greater the uncertainty, the greater the probability of making an error" (p. 339). As such, it is important to recognize the existence of environmental uncertainty from a forensic perspective because human "error" must always be expected when people are performing in environments with irreducible uncertainty (Hammond, 1996). Second, the possible presence of uncertainty suggests that questions about adaptive cognition be addressed and answered at the level of how well tailored or calibrated a performer's judgments or actions are to the environment on average, or at a distributional level of analysis, rather than on an instance-by-instance basis.

4. Embracing Representativeness

The research presented in this book shares with the Naturalistic Decision Making (NDM) paradigm the goal of "conducting one's study with representative samples of subjects, tasks, and contexts to which one wishes to generalize" (Lipshitz et al., 2001b, p. 386). This is illustrated in this volume by the complete reliance on either field observation or the use of dynamic and interactive simulations modeled after the target context of scientific generalization. As will be described by Goldstein in more detail in chapter 2, this methodological commitment is consistent with Brunswik's methodology of representative design. However, as will be illustrated in nearly all of the chapters that follow, this orientation does not preclude the use of systematically designed interventions in representatively designed experiments. This book is filled with examples of investigators using hybrid representative/systematic experimental designs to both foster the generalization of results to a target context and also to test various hypotheses regarding the efficacy of design, training, or aiding interventions and to examine how adaptivity may be influenced by factors such as time stress.

5. A Formal Perspective

The research presented in this volume displays a commitment to abstraction and formalization in the creation of modeling and measurement techniques (also see Byrne & Gray, 2003). The contributors to this volume, as illustrated by their demonstrated commitment to study cognition and behavior in context *and* to perform formal (mathematical or computational) modeling, agree with Todd and Gigerenzer (2001) in noting that the alternatives for describing context-sensitive, adaptive cognition "are not context-free formal modeling versus context-bound informal modeling" (p. 382).

Instead, I hope that the chapters that follow illustrate that it is quite possible to have a deep appreciation for the role of the environmental context in cognition and behavior, yet also to have an appreciation for and ability to formally model the essential aspects of this context. As I have pointed out elsewhere (Kirlik, 2003), research in fields such as human factors and cognitive engineering nearly always begins (or should begin) with a qualitative, naturalistic phase to identify and distill the central features of a target problem to be solved or phenomena to be investigated. Yet if attention then turns directly to creating an intuitive solution or qualita-

tive account (regardless of how well received by stakeholders), without bringing these central features to an abstract level, it is often impossible to know the conditions in which that same solution will prove useful. As such, each cognitive engineering problem will have to be solved largely from scratch. A workable concept of mind useful for cognitive engineering should be one that is fertile in giving rise to a toolbox of formal analysis and modeling techniques, as scientific generalization rides chiefly on the winds of abstraction.

6. A Problem-Solving Perspective

The problem-solving orientation displayed in the research presented herein will be immediately apparent, What might be less obvious in these pages is that in virtually every case researchers had to work with the behavioral situation given to them, and this required them to invent a wide variety of novel extensions and improvisations on the general theoretical perspective uniting these studies within a common intellectual and historical perspective. It is likely that the more important contributions within these chapters lie in the development of these extensions to current theory and method, rather than in any particular empirical findings presented. It may be useful to highlight this aspect of the book at the outset.

To explain, the study of human–technology interaction and the disciplines of cognitive engineering, human factors, and human–computer interaction are changing so rapidly that the practically relevant lifetime of any particular empirical effect or finding is likely to be quite short. In a world continually undergoing reinvention, the specific barriers to adaptive cognition and behavior are likely to change as rapidly as the ecology itself (Kirlik, 2005). As is often the case with the workers and performers cognitive engineers intend to support, our own work as researchers, practitioners, and students of human–technology interaction is one of almost continuous adaptation to novel problems and opportunities. As such, a useful method, model, or measurement technique is likely to have a longer shelf life, as measured by its duration of practical relevance, than any particular experimental result or field observation.

As such, one can only hope that those who might embrace the perspectives on which this book is based and those who might use the methods and models presented here appreciate that these techniques are all works in progress, and additional progress depends on extending and elaborating these tools and techniques. Only then will cognitive engineering come to possess the kind of diverse and reusable toolbox of measurement, analysis, and modeling techniques characteristic of other engineering disciplines.

Conclusion

After the immediately following chapter on theory and method, this volume consists of a set of chapters presenting research adhering to each of the six general themes or perspectives outlined in this chapter. Although it is traditional in a volume such as this to provide an introductory overview and roadmap of the chapters that follow, this is unnecessary for two reasons. First, in chapter 2 Goldstein provides an introduction and tutorial that explicitly situates each chapter by name within its intellectual and historical place in Brunswik's thought and scholarship. Second, I have provided introductory overviews prefacing each of the volume's subsequent sections. Should one desire to gain a quick overview of the substantive contents of the volume, reading Goldstein's chapter and/or reading through each of these brief section introductions should serve this purpose well.

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